An Efficient Medium Access Control Scheme Based on MC-CDMA for Mobile Underwater Acoustic Networks

Jiani Guo, Shanshan Song, Jun Liu, Lei Wan, Yan Zhao, and Guangjie Han

Abstract

Performing effective medium access control (MAC) encounters great challenges for mobile underwater acoustic networks (UANs), because it suffers from low signal-to-noise ratio, Doppler shift, large communication latency, and so on. Multi-carrier code-division multiple access (MC-CDMA) is a promising modulation technique appropriate for solving the above restrictions. In this article, we design a novel MC-CDMA-based cross-layer MAC scheme for mobile UANs, called MCL-MAC, to achieve efficient high-concurrency communication. Specifically, this method allocates spread spectrum sequences dynamically on the basis of velocity, propagation distance, data size, and data grade to improve robustness and flexibility of communication. Moreover, we propose an ant-colony-based optimal channel selection algorithm to decrease inter-carrier interference and inter-symbol interference, which concurrently maximizes energy efficiency and network throughput. In addition, we further propose a solution to solve multihop networks' collisions. Simulation results show that MCL-MAC is more effective than the state-of-the-art methods in mobile UANs.

Introduction

Underwater acoustic networks (UANs) have been widely applied for ocean exploration [1], hydrology surveys [2], and so on. Due to the restricted exploration range of static UANs, autonomous underwater vehicles (AUVs) are adopted to carry out applications with wide coverage [3]. For AUVs, reliable communication is the key foundation to implement underwater tasks.

Medium access control (MAC) protocol is vital for AUVs' reliable communication. Existing underwater MAC methods overcome problems of transmission collisions [4], energy inefficiency [5], throughput insufficiency [6], and so on. However, they are inefficient for mobile UANs.

In comparison to static UANs, communication of mobile UANs imposes three unique challenges: low signal-to-noise ratio (SNR), Doppler shift, and large communication latency. The low SNR decreases probability of data's successful transmission due to the large self-noise of an AUV. Meanwhile, significant Doppler shift caused by the highly dynamic nature of an AUV affects channel quality. Additionally, large communication latency severely restricts timeliness of information, especially for time-sensitive underwater applications.

Multi-carrier code-division multiple access (MC-CDMA) is promising in underwater acoustic communication, which combines orthogonal frequency-division multiplexing (OFDM) and code-division multiple access (CDMA) [7]. Although CDMA has strong anti-interference ability, it is not suitable for frequency diversity. OFDM can implement a frequency diversity scheme; however, it is difficult to quasi-synchronize the transmissions. MC-CDMA combines advantages of these two techniques, which can offer high frequency usage efficiency, flexible resource allocation, and robustness [8]. Unfortunately, there are few research studies regarding MAC algorithms based on MC-CDMA in mobile UANs. Most existing MAC protocols for mobile UANs, like [9], utilize a scheduling algorithm to avoid data collisions. Although the previous work in [10] adopted MC-CDMA to design a MAC protocol, it only selects transmission rate dynamically, without consideration of inter-carrier interference (ICI) in MC-CDMA and underwater environment factors.

In this article, we propose an MC-CDMA-based cross-layer MAC scheme for mobile UANs, called MCL-MAC. By combining physical and MAC layers, MCL-MAC achieves efficient high-concurrency communication, which means energy efficiency, low communication latency, and high throughput. We first design a dynamic spread spectrum sequences allocation algorithm based on velocity, propagation distance, data size, and data grade to improve anti-jamming capability and flexibility of communication. Moreover, an ant-colony-based optimal channel selection algorithm is proposed. It decreases the ICI and inter-symbol interference (ISI), which concurrently maximizes the energy efficiency and network throughput from the whole network perspective. In particular, ISI is interference between symbols due to overlap of multipath at the receiver, and ICI is interference caused by invalid orthogonality between carriers. In addition, we extend our method to multihop networks.

The rest of this article is organized as follows. In the next section, an overview of MCL-MAC is briefly given. Then we present dynamic spread

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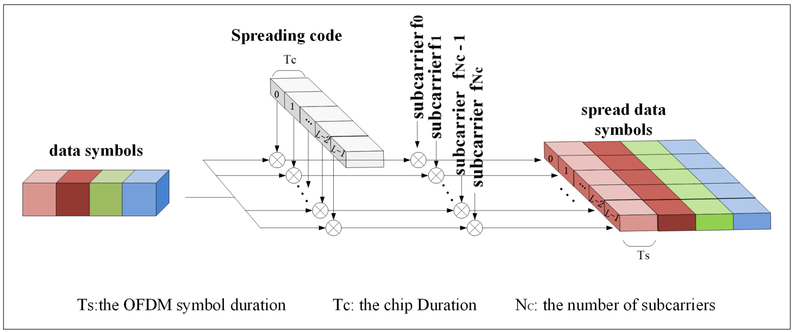

FIGURE 1. The schematic of MC-CDMA.

spectrum sequences allocation, optimal channel selection, and extension of multihop networks, respectively. Following that, we evaluate the performance of MCL-MAC according to simulation results. Finally, our conclusions are offered.

Description of MC-CDMA-Based Cross-Layer MAC

In this section, we discuss the MC-CDMA-based MCL-MAC scheme. As shown in Fig. 1 [11], MC-CDMA is a multi-carrier modulation technique. Take a blue data symbol as an example; MC-CDMA spreads it by multiplying a given spreading code in the frequency domain. Then the spread blue data symbol is mapped to parallel narrowband subcarriers. This concept is proposed with OFDM, which is efficient for bandwidth utilization. In MCL-MAC, we design the dynamic spread spectrum sequences allocation algorithm, optimal channel selection algorithm, and extensional solution for multihop networks.

Overview of MC-CDMA-Based Cross-Layer MAC

AUV systems are generally used for underwater cooperative operations, such as marine data collection, pipeline monitoring, and military applications. The characteristic of these applications is that multiple subtasks are expected to perform simultaneously and not interfere with each other. In order to meet this demand, cluster topology is adopted. In MCL-MAC, multiple AUVs are divided into different clusters, and each cluster has a cluster head node and member nodes. The member nodes are one-hop neighbors of their cluster head node. MCL-MAC consists of four stages:

- Cluster head broadcast
- Uplink communication request
- Downlink communication response
- Data transmission, as shown in Fig. 2a

Cluster Head Broadcast: In this stage, we suppose the cluster head node has member nodes' location information. It calculates appropriate sending time for each member node, which guarantees that packets from member nodes to the cluster head node are received simultaneously. Then the cluster head node broadcasts this information through a packet, defined as BRO, that is transmitted by all subcarriers.

Uplink Communication Request: After receiving the BRO packet from its cluster head node, a member node sends a communication request packet, called REQ, at the sending time acquired from BRO. Combined with MC-CDMA, multiple member nodes' REQ packets are decoded as one packet, and the cluster head node can distinguish them via respective spreading codes. It is important that different member nodes' REQ packets arrive approximately simultaneously at the cluster head node, in which case the slightly asynchronous arrival caused by timing error and multipath of each node can be compensated by the cyclic prefix of OFDM systems. ISI could be avoided as long as the length of the cyclic prefix is greater than the sum of the maximum time difference of asynchronous arrivals and the multipath delay spread.

Downlink Communication Response: It is worth noting that data packets will not be transmitted with all subcarriers like control packets in our proposed scheme. The three major reasons are:

- In mobile UANs, different member nodes could have different relative speeds than the cluster head node, which will make the received signal at the cluster head node suffer from multiple distinct Doppler distortions, hence destroying the orthogonality between subcarriers and introduce ICI.
- The channel conditions and data grades for different member nodes are different.
- Through assigning different member nodes with different non-overlapping subcarriers, the frequency selectivity of underwater acoustic communication channels can be better exploited.

In order to maximize communication efficiency, the cluster head node classifies member nodes on the basis of REQs' information. Then the classified member nodes are allocated different numbers of subcarriers. After that, the cluster head node broadcasts an Acknowledgment packet, called ACK, to report the allocation result.

Data Transmission: Member nodes transmit their data packets based on the schedule received from the ACK packets, as shown in Fig. 2b. To reduce ICI and ISI, these packets arrive at the cluster head node simultaneously like REQ packets. Then all members wait for the next round communication that begins with BRO.

Dynamic Spread Spectrum Sequences Allocation

In MCL-MAC, to combat the challenging channel condition and enhance robustness, member nodes with longer latency, severe Doppler shift, and higher data grade should be assigned longer spread spectrum sequences. Before allocating the spread spectrum sequences, first, member nodes are classified on the basis of the following parameters: distance, relative velocity, data size, and data grade. Because distance influences signal attenuation, relative velocity is related to Doppler shift; data size affects packet error rate for given bit error rate. In addition, we consider urgency degree of messages. Significant information, like equipment failure and pipeline leakage, needs to be transmitted more accurately and rapidly than ordinary data information.

Packets are divided into four grades (1, 2, 3, 4), denoted as G. The packet grade increases as G descends. Assuming a cluster has N member nodes, we denote $W = w_d, w_v, w_s$ as weights of transmission distance d_i, relative velocity v_i, and data size s_i, respectively. Spearman correlation [12] is adopted to calculate the value of W based

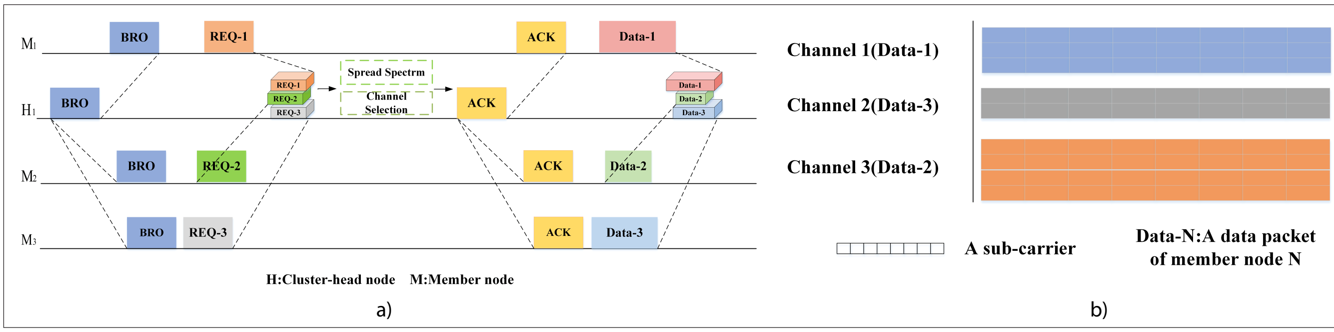

FIGURE 2. Four transmission stages of MCL-MAC: a) transmission between the cluster head node and member nodes; b) data transmission with subcarriers.

on a time-varying underwater acoustic channel model. After receiving REQ packets, the cluster head node first normalizes d_i, v_i, s_i, and calculates $L = l_1, l_2, l_3, \ldots, l_n$ as follows:

$$l_i = (w_d \cdot d_i + w_v \cdot v_i + w_s \cdot s_i)^{G_i}, \tag{1}$$

where $i = 1, 2, \ldots, n$ ($1 \leq n \leq N$, denotes the numbers of REQ packets).

For each member node, the length of spread spectrum sequences is equal to the number of subcarriers. Supposing the number of subcarriers N_c is fixed, we divide it into three orders of magnitude $N_c/4$, $N_c/8$, and $N_c/16$. L is sorted from large to small, and the node with larger l_i should be allocated more subcarriers. On the basis of the sorted L, a cluster head node classifies member nodes through a K-means algorithm [13]. Then the nodes from the same classification are assigned the same number of subcarriers.

However, the classical K-means clustering algorithm may have two hidden problems. First, the sum of all nodes' subcarriers exceeds N_c, which results in throughput insufficiency. Second, the sum of all nodes' subcarriers is less than N_c, which affects channel utilization. Nodes are divided into different sets based on number of subcarriers, and sorted in descending order by l_i in each set. In the first case, start from the set with the largest number of subcarriers; nodes with smaller l_i should decrease subcarriers' numbers until the sum of nodes' subcarriers do not exceed N_c. Analogously, start from the set with the smallest number of subcarriers; nodes with higher l_i should be assigned more subcarriers in the second case until extra subcarriers are not enough for one more node.

Optimal Channel Selection Algorithm

After assigning the number of subcarriers, we design an ant-colony-based [14] optimal channel selection algorithm for the cluster head node to allocate specific subcarriers to each member node. For a single node, a channel with high SNR or low energy consumption is assigned based on its data grade. Meanwhile, the algorithm maximizes energy efficiency from the perspective of the whole network.

To eliminate ICI and ISI, subcarrier allocation follows a unique and continuous rule. The number of available channels for one node is a quotient of total subcarriers and its length of spread spectrum sequence. We set various transmission modes in our protocol to improve communication flexibility. For different modes, there is a discrepancy in block size, but transmission time of all blocks are the same. In order to decode a data block correctly, guard time should be set between two adjacent blocks. The cluster head node selects the transmission mode for a node on one channel based on its SNR value. In addition, considering the serious impacts of long transmission delay, nodes with abundatnt data should utilize the maximum transmission rate to decrease end-to-end delay. Therefore, the block size of a node on one channel can be defined as follows:

$$b_{ij} = \begin{cases} max\{b_{ij}^m, C_{ij} \cdot trans_t\} & s_i > \frac{\sum_{i=1}^n s_i}{n} \\ b_{ij}^m & otherwise, \end{cases}$$

where b_{ij}^m is the block size of node i on channel j in mode m, C_{ij} is the max rate calculated by Shannon theory of node i on channel j, and s_i is the data size of node i.

In this algorithm, ants release pheromones on passing channels. Due to the increasing pheromones, the number of ants that choose the same channel increases gradually. Finally, the ant colony will gather in the optimal channel under effect of positive feedback. In the following, we present the process in detail.

In each transmission round, nodes are sorted in descending order based on their number of subcarriers. For two nodes that have the same number of subcarriers, the one with a higher-grade packet ranks first. An ant selects unallocated channels for each node in order. A node that has not been allocated a channel should wait for the next transmission round. Otherwise, the ant allocates a channel based on maximum product of matching degree and prior information. In particular, matching degree is an increment of a network's energy efficiency, and prior information is related to packet grade of the current node, which means that a high-grade packet is concerned with channel quality, and a low-grade packet focuses on energy consumption.

The cluster head node calculates energy efficiency of the current ant's solution and saves it in a list, called the tabu list. Repeat the steps above until all ants accomplish their tasks, and one complete iteration is accomplished. After each iteration, the plan with the maximum energy efficiency found by ants is updated, and all tabu lists are then emptied. When all ants generate the same allocation, or the iteration reaches the maximum number, the algorithm stops and returns the optimal result.

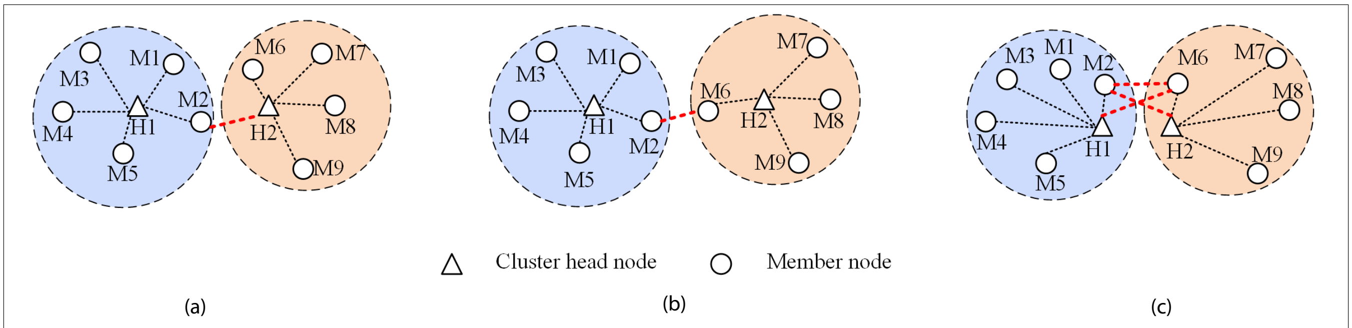

FIGURE 3. Collision types for multihop networks: a) cluster head-member collision; b) member-member collision; c) hybrid collision.

Extending MCL-MAC to Multihop Networks

In this section, MCL-MAC is extended to general scenarios, multihop networks. We solve the collisions among clusters in this article.

Cluster Head-Member Collision and Member-Member Collision: Appropriate solutions for different collision situations are described in the following.

Cluster Head-Member Collision: In Fig. 3a, node M_2 is a member of cluster head H_1, but also a neighbor of cluster head H_2. If node M_2 sends data packets to cluster H_1 during the receiving slot of cluster head H_2, the intra-cluster communication of the whole cluster H_2 will be affected. To eliminate this type of collision, in the initial stage of current communication, node M_2 first estimates whether its transmission to cluster head H_1 will interfere with cluster M_2 on the basis of BRO packets from cluster head H_1 and cluster head H_2. If there is a collision and node M_2's packet grade is low, node M_2 backs off, and its back-off number increases by 1. Otherwise, if node M_2's packet has high grade or its back-off number reaches the maximum value, cluster head H_2 postpones its intra-cluster transmission until it receives the data packet from node M_2.

Member-Member Collision: As shown in Fig. 3b, there is a conflict between node M_2 and node M_6, which only affects the transmission of these two member nodes. In order to avoid such conflicts, before sending ACK packets, cluster head H_1 first exchanges its schedule with cluster head H_2 and adjusts the sending time of member nodes (ASTM). Then the cluster heads reply with ACK packets with the updated schedule.

Specifically, during the clustering period, node M_2 and node M_6 can know that they are neighbors but belong to different clusters. Cluster head H_1 can obtain the propagation delay between node M_2 and node M_6 via REQ packets from M_2, and the same is true for cluster head H_2. In the ASTM period, cluster head H_1 sends a notice packet to cluster head H_2, which includes sending time assigned by cluster head H_1 to node M_2, transmission delay of node M_2, and propagation delay between node M_2 and node M_6. From the notice packet, cluster head H_2 can calculate the receiving time of a packet from node M_2 to node M_6.

In this case, there may be a conflict when node M_6 fails to send a packet at the appointed time due to its incomplete reception from node M_2. In this case, cluster head H_2 should postpone the sending time of all member nodes. Cluster head H_2 reports its updated schedule to cluster head H_1; then the two cluster heads manage intra-cluster communication with their latest schedules.

If a general network includes both collisions, *cluster head-member collision* should be disposed of first. As described in Fig. 3c, node M_2 conflicts not only with node M_6 but also with cluster head H_2. By first eliminating the collision between a cluster head and a member node, one of the conflicting member nodes or one of two whole clusters will keep silent. Then the network can avoid *member-member collision*.

Performance Evaluation

In this section, we evaluate the performance of MCL-MAC with simulations. Aqua-sim-ng [15], a NS-3-based UAN simulator, has been used as our simulation tool.

Simulation Settings

In our simulation, we set a 20-node network, and all nodes are randomly distributed in a 4000 m × 4000 m × 500 m area. In order to evaluate the efficiency of MCL-MAC protocol in a mobile environment, nodes are set to move freely in an X–Y two-dimensional plane. The movement speed obeys uniform distribution ranging from 0.5 to 1.5 m/s. The propagation speed of acoustic signal is 1500 m/s, and the preamble is 0.5 s, which is used to estimate quality of channel and time synchronization. The communication range is set to 1500 m, and the total number of sub-carriers is 512. The data packet sizes range from 100 B to 300 B, and the number of max retransmissions is set to 3. In our experiments, each simulation lasts 2000 s.

Dynamic Spread Spectrum

From Fig. 4a, we design some rays with various data sizes, distances, and velocities, and simulate an underwater channel. Then we calculate the Spearman coefficient between each parameter and channel impulse response. After numerous experiments, we obtain w_v = 0.625, w_d = 0.189, and w_s = 0.186.

According to the information of REQ packets and W, the cluster head node calculates the value of L and allocates different lengths of spread spectrum sequences to member nodes via a subcarriers allocation algorithm. The allocation result is shown in Fig. 4b; some nodes that are far away from the cluster head node have fewer subcarriers. This result demonstrates that our algorithm can allocate spread spectrum sequences on the basis of number of member nodes, propagation distance, velocity, data size, and data grade, not just based on the propagation distance.

Performance of MCL-MAC

In order to further verify the performance of our protocol, we compare the main network metrics of MCL-MAC with a random-access-based MAC (ALOHA) and a handshake-based MAC (S-FAMA).

Throughput, Energy Consumption, and Energy Efficiency

Impacts of Input Traffic: In this set of simulations, we compare the performance of these three protocols by varying the total input traffic from 0.01 pkt/s to 0.1 pkt/s.

From Fig. 5a, it can be observed that MCL-MAC transmits more packets than S-FAMA and ALOHA. This is because the collision of control packets is considered in MCL-MAC. In addition, multiple packets are allowed to be sent together with just one round of REQ/ACK handshake in MCL-MAC, which can improve the throughput of the system substantially.

From Fig. 5b, MCL-MAC, as a protocol with multiple types of control packets, consumes less energy than S-FAMA. This is because in MCL-MAC, the collision of control packets is considered, and the optimal channel selection algorithm is used to allocate channels. Because control packets and large amounts of data packets are transmitted, the energy consumption of MCL-MAC is higher than ALOHA's.

From Fig. 5c, we can observe S-FAMA has extremely low energy efficiency. This is because the collision of control packet makes the handshake protocol inefficient. ALOHA lacks the ability to avoid the collision of data packets and thus is not efficient enough. As for MCL-MAC, we can see that the energy efficiency is low when λ = 0.01 pkt/s. Due to low input traffic, there may be no REQ packets to reply to BRO packets, and this empty communication round may occur many times. Therefore, the energy efficiency of MCL-MAC is a bit lower than that of ALOHA. As input traffic increases, MCL-MAC is more energy-efficient. This is because collisions in ALOHA become serious, and retransmission wastes more energy. Meanwhile, MCL-MAC transmits packets concurrently and considers total network energy efficiency when it assigns channel resource.

Impacts of Node Density: In this set of simulations, we set the total input traffic as 0.1 pkt/s and change the number of network nodes n from 4 to 20. Then the input traffic of each node is $0.1/n$ pkt/s. From Fig. 5d, the throughput of all these three protocols increases as the size of node density becomes larger. In MCL-MAC, intra-cluster collision and inter-cluster collision can be eliminated by the optimal channel selection algorithm and ASTM, which achieve better throughput than other protocols.

From Fig. 5e, MCL-MAC consumes more energy than other protocols when the number of nodes is small. The reason is the same as Fig. 5c: there may be an empty communication round, and excessive BRO packets consume more energy. However, as the number of nodes increases, the energy consumption of S-FAMA and ALOHA grows much faster. This is because the network generates more packets, which causes more collisions in S-FAMA and ALOHA. As for MCL-MAC, the increase in energy consumption is due to more packets being transmitted.

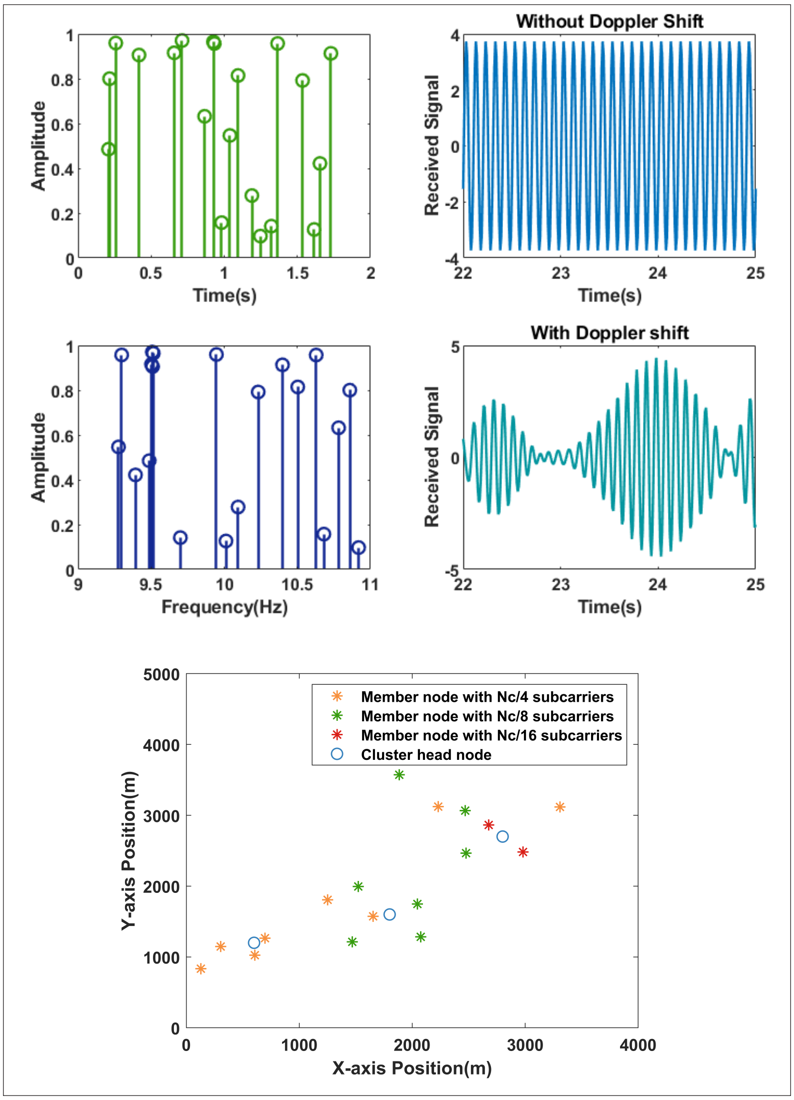

FIGURE 4. Channel simulation and dynamic spread spectrum: a) channel simulation; b) dynamic spread spectrum.

From Fig. 5f, compared with other protocols, MCL-MAC supports multiple packets to be transmitted in the same round without collisions, and the energy efficiency of the protocol is high and steady no matter the number of nodes in the network.

Delivery Ratio and Delay: In this set of simulations, we set the number of nodes in the network as 20. Then we observe the delivery ratio and end-to-end delay by changing the input traffic from 0.01 pkt/s to 0.1 pkt/s.

From Fig. 6a, MCL-MAC can guarantee larger delivery ratio of 1-grade data packets than other protocols. In MCL-MAC, the 1-grade packet can get larger spread spectrum gain and a channel with higher quality. Therefore, MCL-MAC performs the highest delivery ratio of 1-grade data packets.

From Fig. 6b, the delivery ratio of all data packets decreases with the increasing input traffic in S-FAMA and ALOHA. This is similar to the explanation in Fig. 5a. As for MCL-MAC, the collisions of control packets can be eliminated by MC-CDMA, and we also design algorithms to resolve intra-cluster and inter-cluster collisions. Thereby, the delivery ratio in MCL-MAC is the highest, and it does not change significantly.

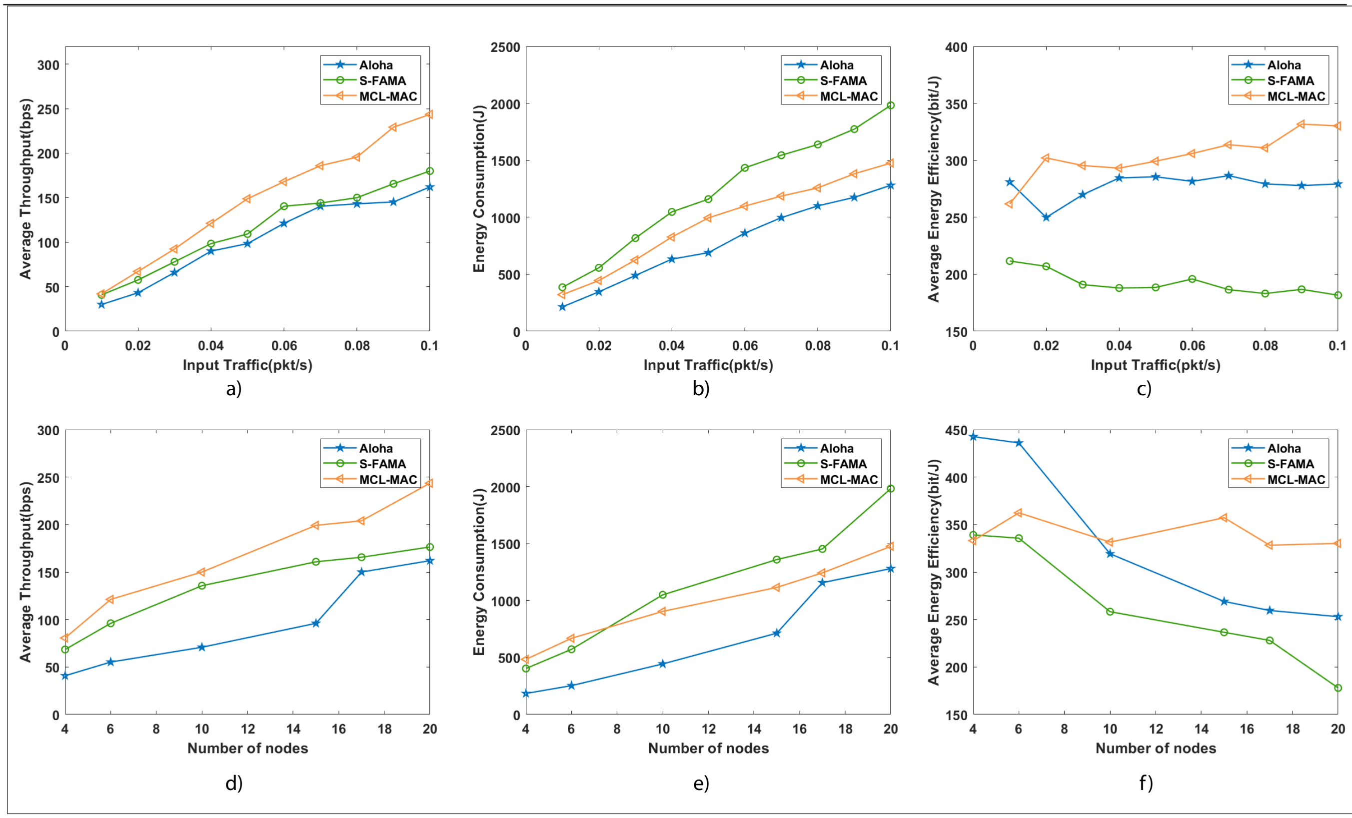

FIGURE 5. Throughput, energy consumption, and energy efficiency of MCL-MAC and benchmark methods: a) average throughput with variational *l*; b) energy consumption with variational *l*; c) energy efficiency with variational *l*; d) average throughput with variational nodes; e) energy consumption with variational nodes; f) energy efficiency with variational nodes.

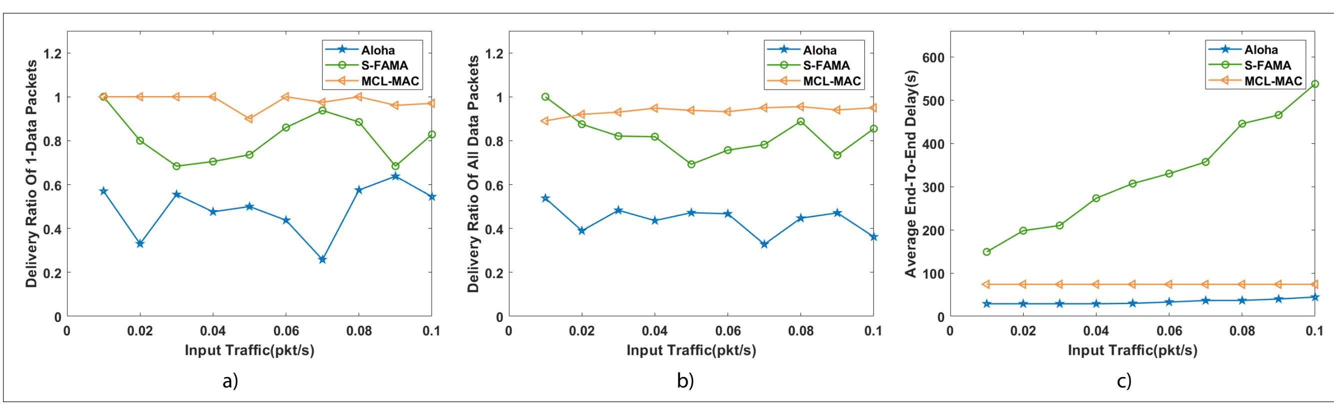

FIGURE 6. Delivery ratio and delay of MCL-MAC and benchmark methods: a) highest-grade data delivery ratio; b) all data delivery ratio; c) end-to-end delay.

From Fig. 6c, the collisions of control packets in S-FAMA introduce extra delay. As for ALOHA, packets can reach the destination with small end-to-end delay. This is because the simple design of the protocol, and lost packets are not included in delay calculation. As a receiver-centric MAC, communication commands are initiated by the receiver in MCL-MAC. Therefore, the end-to-end delay does not change significantly in Fig. 6c. We can also see that the end-to-end delay of MCL-MAC is satisfactory. This is because multiple types of collisions are considered in MCL-MAC, as discussed for Fig. 6b.

Conclusion and Future Work

In this article, we present MCL-MAC to achieve efficient high-concurrency communication for mobile underwater acoustic networks. The key idea of MCL-MAC is the combination of MC-CDMA in the physical layer. To improve the anti-interference capability and flexibility of communication, spread spectrum sequences are assigned dynamically on the basis of velocity, propagation distance, data size, and data grade. Moreover, an ant-colony-based channel selection algorithm is proposed to optimize throughput, energy consumption, and energy efficiency. In addition, a scheduling solution is designed for multihop networks to eliminate collisions among clusters. Extensive simulation results demonstrate that MCL-MAC is a promising solution for mobile underwater acoustic networks.

Future Work

MCL-MAC has empty communication rounds at present due to the fixed broadcast interval of the cluster node. In the future, we can design an adaptive polling scheme to avoid this problem and make the protocol more efficient in large-scale heterogenous underwater acoustic systems.

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Acknowledgments

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